Acceleration and loss of relativistic electrons during geomagnetic storms

G. D. Reeves, K. L. McAdams, R. H. W. Friedel

Space and Atmospheric Sciences Group, Los Alamos National Laboratory, Los Alamos, NM 87545

T. P. O'Brien

Space Sciences Department, The Aerospace Corporation, Los Angeles, CA 90009

Abstract. We analyze the response of relativistic electrons to the 276 moderate and intense geomagnetic storms spanning the 11 years from 1989 through 2000. We find that geomagnetic storms can either increase or decrease the fluxes of relativistic electrons in the radiation belts. Surprisingly, only about half of all storms increased the fluxes of relativistic electrons, one quarter decreased the fluxes, and one quarter produced little or no change in the fluxes. We also found that the pre-storm and post-storm fluxes were highly uncorrelated suggesting that storms do not simply "pump up" the radiation belts. We found that these conclusions were independent of the strength of the storm (minimum Dst) and independent of L-shell. In contrast, we found that higher solar wind velocities increase the probability of a large flux increase. However, for all solar wind velocities both increases and decreases were still observed. Our analysis suggests that the effect of geomagnetic storms on radiation belt fluxes are a delicate and complicated balance between the effects of particle acceleration and loss.

1. Introduction

The dynamics of the radiation belts have received considerable attention in recent years because of their impact on life in our technology-based society and because of the fundamental and unresolved scientific questions about the acceleration and loss of radiation belt particles. The most dynamic population in the radiation belts is the population of relativistic electrons ($E > \sim 1$ MeV) in the outer electron belt. The most dramatic changes in the relativistic electron populations occur during enhanced periods of geomagnetic activity. Therefore it is of considerable scientific and practical interest to better understand the relationship between changes in the radiation belts and geomagnetic storms.

As early as 1966 Williams related periodic increases in the trapped relativistic electron populations to increases in the solar wind kinetic energy density. Paulikas and Blake [1979] established the well-known relationship between enhanced solar wind velocity and increases in relativistic electron fluxes. Later Blake et al. [1997] showed that southward interplanetary magnetic field along with high speed solar wind was more effective at producing relativistic electron enhancements than high solar wind velocity alone. The first predictive numerical model of relativistic electron flux enhancements was also based on linear prediction filters using the Kp index which is a broad measure of geomagnetic activity [*Nagai.,* 1988].

In a predecessor to this study, Reeves [1998] examined three years (1992 through 1994) of relativistic electron fluxes from geosynchronous orbit and compared changes in those fluxes with geomagnetic storm activity measured by the Dst index. Reeves found that each distinct electron enhancement could be clearly associated with a distinct decrease in the Dst index which clearly established a connection between geomagnetic storms and relativistic electron enhancements. Reeves also found that approximately 10% of clearly identified storms were not accompanied by increases in the geosynchronous relativistic (1.8-3.5 MeV) electron fluxes. Additionally, while larger relativistic electron fluxes tended to occur during larger storms, the correlation was quite weak. (We also note that, in contrast to this study, Reeves [1998] included storms with minimum Dst as weak as –20 nT.)

All the studies cited above focused on increases in relativistic electron fluxes. However, dramatic decreases in electron fluxes can also be observed during geomagnetic storms. The most common decrease is a temporary, adiabatic 'dropout' of electron fluxes associated with the build-up of the storm-time ring current. This adiabatic effect is known as the 'Dst Effect' [e.g. *Kim and Chan*, 1997]. A purely adiabatic response would return the relativistic electron fluxes to their pre-storm levels once Dst had fully recovered. However, during some storms the electron fluxes never regain their pre-storm levels [e.g. *Onsager et al.,* 2002; *O'Brien et al.,* 2001a].Friedel et al., [2002] provide a more complete review of acceleration and loss mechanisms and associations with various types of geomagnetic activity.

In this study we examine a full solar cycle of data (1989-2000) to quantify the relationship between geomagnetic storms and relativistic electron flux increases and decreases.

2. Data sets

As a broad measure of geomagnetic activity we use the 1-hour resolution Dst index for the years 1989 through 2000 [Courtesy of Kyoto University]. (Preliminary Dst data were used for 1999-2000.) Because complete solar wind data is not available for this entire time period we do not apply any corrections for magnetopause currents (pressure correction). Similarly we use 1-hour solar wind velocity measurements (when available) from the OMNI database [Courtesy of the National Space Science Data Center].

Geosynchronous data are from the Los Alamos National Laboratory (LANL) space environment monitors [e.g. *Reeves et al.,* 1996]. We use data from the 1.8-3.5 MeV channel of the ESP detector [Meier et al., 1996]. To minimize the effects of daily local time variation caused by magnetic field asymmetries [e.g. *Reeves et al.,* 1998a] we apply a statistical reconstruction of the fluxes to a common local time which is chosen to be noon. This is the same technique and the same data set used by O'Brien et al. [2001b]. One-hour resolution data from multiple satellites are averaged to obtain a single consistent time series.

A broader measurement of the radiation belts is provided by data from the HIST instrument on the POLAR satellite [*Blake et al.,* 1995]. POLAR is in an elliptical orbit with apogee at approximately 9 R_E and an orbital period of about 18 hours. In 1996 apogee was at nearly 90° north latitude and by 2002 apogee had precessed down to approximately 0°. We use electron fluxes from the 1.2-2.4 MeV channel sorted by L-shell. To minimize the effect of errors in calculating L in the asymmetric geomagnetic field [e.g. *Selesnick and Blake,* 2000] we use only data from the northern hemisphere, inbound quadrant of the POLAR orbit. POLAR data are only available from late 1996 onward and we use data through 2000.

Throughout this study we calculate “L” using the Kp=2 version of the static Tsyganenko 1997 magnetic field model. Therefore “L” here should be considered to be an indication of spatial location rather than an invariant of particle drift motion. Current magnetic field models cannot accurately represent the global magnetic field during storms so it preferable in this study not to introduce any model-dependent time variations.

3. Increases and decreases in relativistic electron fluxes during storms

Throughout this analysis we start by identifying geomagnetic storms and then investigate the relativistic electron response. In contrast to the earlier study of Reeves [1998], we use a fixed definition of geomagnetic storms as distinct intervals during which the minimum value of the Dst index is less than -50 nT. Gonzalez et al. [1994] define these as moderate (Dst < -50 nT) or intense (Dst < -100 nT) geomagnetic storms.

Plate 1 shows the relativistic electron fluxes (1.2-2.4 MeV) measured by POLAR as a function of L-shell and time for the year 1997. Also shown are the Dst index and the solar wind velocity (OMNI data). The -50 nT Dst threshold is indicated with a red line and we see that there were 21 storms during 1997 which met our criteria (including one beginning on December 30). Many, but not all, of these storms were associated with relatively high speed solar wind.

Plate 2 shows three examples of the relativistic electron response to geomagnetic storms. Plate 2a shows the interval from January 1 to February 25, 1997 which includes the well-known January 10, 1997 storm [e.g. *Reeves et al.,* 1998a, 1998b; *Li et al.,* 1998]. This storm is typical of the storms that most studies have analyzed to date. A brief decrease of the relativistic electrons is observed in association with the build-up of the ring current but is quickly followed by a rapid increase of the electron fluxes over a broad range of L-shells. (Reeves et al., [1998b] showed that the increase is not simultaneous at all L-shells but the differences are short compared to the POLAR satellite revisit interval.)

The storm in May 1999 (Plate 2b) shows a quite different response. Again there is a rapid decrease in fluxes at the storm main phase but, in this event, the fluxes never recovered to their pre-event levels. This cannot be explained by adiabatic processes and must therefore represent a true loss of particles. We note that the decrease in fluxes was observed over a broad range of L-shells down to at least L=4. In February, 1998 (Plate 2c) a geomagnetic storm which qualifies as “intense” (Dst = -100 nT) by the Gonzalez et al. definition, produced a relatively small change in the relativistic electron fluxes.

In Plate 2 we have marked each event with a vertical bar that is color-coded to indicate the classification of the event: red for “increase”, blue for “decrease”, and green for “no change”. For completeness we note that there are obvious relativistic electron enhancement events which are not part of our analysis because the minimum Dst was greater than -50 nT or a key data set was missing. An example of such an event is seen in the middle of Plate 2a. However, the aim of this study is to show the electron response to events which are unambiguously “storms”.

3.1 Geosynchronous statistics

To statistically analyze the relativistic electron response to geomagnetic storms we need to quantify the amount of increase or decrease in the fluxes. To do so, we first examine the fluxes at geosynchronous orbit which is at a fixed L-shell, $L \approx 6.6$. The 24-hour period centered on the time of minimum Dst is considered the ‘day of the storm’ and is not included in the analysis. We define the ‘pre-storm flux’ as the maximum flux of 1.8-3.5 MeV electrons in the 1-3 days prior to storm (not including the day of the storm). We define the ‘post-storm flux’ as the maximum flux of 1.8-3.5 MeV electrons in the 1-5 days after the storm. We define the relative change as the ratio of the of the pre-storm to post-storm fluxes. We define “No Change” to mean that the relative change was less than a factor of 2 change in fluxes up or down. By these criteria 10 of the 21 events in 1997 (Plate 1) were classified as geosynchronous “increases”, 5 were classified as geosynchronous “decreases”, 5 were classified as “no change” and one storm, on May 15, had missing data and was not included in the analysis.

In Plate 3a we plot the post-storm flux against the pre-storm flux and color each point: red for “increase”, blue for “decrease”, and green for “no change”. One clear conclusion from this plot is that the post-storm fluxes are essentially uncorrelated with the pre-storm fluxes. Any given pre-storm flux could result in either high or low fluxes after the storm. Likewise any given post-storm flux could have been preceded by either high or low pre-storm levels.

Plate 3b shows the distribution of events as a function of the change in flux (the ratio of post-storm to pre-storm fluxes). Over one entire solar cycle from 1989 through 2000 there were 276 storms with Dst < -50 for which we had complete geosynchronous data (noon reconstructed fluxes). Of those 276 storms, 145 storms (or 53%) resulted in an increase in geosynchronous fluxes of more than a factor of 2. Another 53 storms (19%) resulted in a flux decrease of more than a factor of 2. For the remaining 78 storms (28%) changed the fluxes by less than a factor of 2 in either direction.

Thus, we find that only about half of all storms produce a significant increase in relativistic electron fluxes (i.e. greater than a factor of 2). We also find the somewhat surprising result that approximately 1 in every 5 storms will decrease the fluxes by more than a factor of 2.

It is also interesting to note the distribution of extreme changes. Six of the storms produced an increase in fluxes of more than two orders of magnitude and one produced an equally dramatic decrease.

It is important to point out that we purposefully chose different length intervals for the pre-storm and post-storm maximum flux determinations even though this has an effect on the statistics presented here. The interval 1-5 days was chosen for the pos-storm fluxes to make sure there was sufficient time to reach the maximum flux level. Shorter intervals missed the peak electron fluxes for some storms. A shorter interval of 1-3 days (half as long) was chosen for the pre-storm determination because it is the fluxes immediately prior to the storm that are of primary interest. The longer interval for post-storm fluxes (96 hours) compared to pre-storm fluxes (48 hours) skews the distribution such that it is statistically more likely that the post-storm fluxes will be higher even if the variations are random. However we feel that the criteria used here best represent the changes in electron fluxes produced during storms.

3.2 Are larger storms more likely to produce increases?

It is commonly assumed that larger storms (more negative minimum Dst) are more likely to produce large enhancements of the radiation belt fluxes. To test this assumption we binned the 276 storms in our study according to their minimum Dst. The bins were –50 to –75 nT, -75 to –100 nT, -100 to –150 nT, and –150 to –400 nT. Two bins represent "moderate storms" and two represent "intense storms". (Note that the bins are not of equal width but were chosen to have a significant number of events in each bin.)

In Plate 4a we plot the cumulative probability distribution as a function of the flux ratio (post/pre) for each range of Dst. The cumulative probability is the probability that the flux ratio will be less than a given value (e.g. it integrates the probability up to that value). The maximum difference in the cumulative probability curves, Δ, is marked in each plot and is a measure of how different the probabilities are and S is a measure of how likely it is that the difference is random.

We see from Plate 4a that the probability distributions for all four curves are essentially identical. Therefore the probability that the fluxes will increase (or decrease) by a given amount is essentially independent of the minimum value of Dst. Larger storms are not more likely to increase the relativistic electron fluxes than smaller storms.

Although we do not show it here we note that an analysis of the same storms shows that larger storms are also not more likely to produce a high absolute flux level. Those results will be presented elsewhere.

3.3 Does the chance of an increase depend on L-shell?

In this paper we present a statistical analysis of the relativistic electron fluxes measured at geosynchronous orbit. It is relevant, therefore, to ask if the geosynchronous fluxes are representative of the radiation belt response as a whole. We have performed a similar analysis to the one presented here on electron fluxes measured at different L-shells and we find that the results are essentially independent where the electron fluxes are measured.

In this brief report we show only the cumulative probability as a function of flux ratio for fluxes measured by the POLAR satellite at L=4, 5, 6, and 7 (Plate 4b). Each bin is L= ±0.2 wide. The probability curves for L=4, 5, and 6 are nearly identical and only the L=7 curve is significantly different and only for a certain range of flux ratios.

As we see from Plate 1 the fluxes measured by POLAR near L=7 are very low and POLAR is quite far off the equator when it crosses those L-shells. Therefore it is unclear at this stage whether the difference in the L=7 curve is meaningful.

For all L-shells (4, 5, 6, and 6.6) we find that about 50% of all storms increase the fluxes by more than a factor of 2, approximately 20-30% of the storms decrease the fluxes by more than a factor of 2, and the remaining 20-30% produce no significant change at that given L-shell.

We can see in Plates 1 and 2 that a given storm may increase fluxes at one L-shell while decreasing fluxes at a different L-shell. However, when we look at a fixed L-shell we find that the statistical probability of increase or decrease in the outer electron belt is independent of where the measurement is made.

3.4 Do high solar wind velocity storms produce more increases?

The relationship between high-speed solar wind streams and increases in the relativistic electron fluxes in the outer belts is probably the most widely known result concerning the radiation belts. In Plate 4c we examine that relationship for these storms by now separating the events according to the maximum solar wind velocity observed during the event (which could occur either before or after the storm main phase).

Four bins of solar wind velocity are plotted: 0 to 500 km/s, 500-600 km/s, 600-700 km/s, and 700 to 1100 km/s. In this analysis we see that there is a higher probability of increasing fluxes for higher solar wind velocities than for lower velocities. The maximum difference in the curves, Δ, is 31% which is very unlikely to be random (S=1%). We also see that the higher-velocity curves appear shifted to the right relative to the lower-velocity curves. This means that throughout the distributions the higher-velocity events produce larger increases in flux.

Nevertheless we also point out that both high-speed and low-speed solar wind drivers can and do produce both increases and decreases in flux. Looking at the portion of the curves in Plate 4c which lie below 10^0 we see approximately 25-35% of all events produce no change or a decrease in fluxes regardless of solar wind velocity. We also note that the one storm that decreased the fluxes by a factor of 135 fell in our second-highest velocity bin with Vsw=654 km/s.

We note that these results may be biased by our assumption of a static magnetic field configuration. The effects of solar wind velocity on the magnetic field are systematic not random. However, the conclusions still appear to be sound.

Since solar wind velocity does appear to affect that chance of producing a radiation belt flux increase, we also investigated whether storms at solar minimum were more likely to produce flux increases than storms at solar maximum. We used the years 1992-1994 for solar minimum and 1990, 1999, and 2000 for solar maximum. While these intervals do not precisely correspond to the sunspot cycle they do compare three years when recurrent high-speed streams from equatorial coronal holes were observed with three years when they were typically were not.

Plate 4d shows that, indeed, storms in our “solar minimum” years were more likely to produce larger increases in flux than storms in our “solar maximum” years but, that difference is not as large or as significant as when solar wind velocity is explicitly used as a discriminator. This is to be expected since both high- and low-speed solar wind drivers can be observed at either phase of the solar cycle. We also again find that for storms at both phases of the solar cycle both increases and decreases of the radiation belt fluxes are observed.

4. Conclusions

We have examined the response of relativistic electrons (≈1-3 MeV) in the outer radiation belts to 276 geomagnetic storms spanning the 11 years from 1989 to 2000. By definition we chose storms that were “moderate” (Dst < -50 nT) or “intense” (Dst < -100 nT). We compared the fluxes observed before the storm to the fluxes observed after the storm and sorted the data according to Dst, L-shell, solar wind velocity, and solar cycle.

The most significant conclusion from this study is that a given geomagnetic storm can either increase or decrease the fluxes of relativistic electrons in the radiation belts.

We determined the probability that a given storm will increase or decrease the fluxes of relativistic electrons. At geosynchronous orbit (L≈6.6) we found that about half (53%) of the geomagnetic storms (145 events) increased the fluxes by more than a factor of two. About one in five geomagnetic storms (19%, 53 events) decreased the fluxes by more than a factor of two. The remaining storms (28%, 78 events) produced changes that were less than a factor of two either up or down.

While it has been known that some storms produce a decrease in geosynchronous electron fluxes the number of such storms is a new and somewhat surprising result with important implications for the study and understanding of radiation belt dynamics. We also note that these probabilities, if anything, underestimate the number of storms that decrease the electron fluxes. By design, our post-storm interval is twice as long as our pre-storm interval which increases the probability that a flux increase would be observed in a random sample of times.

We investigated the hypothesis that larger storms (lower minimum Dst) would be more likely to increase relativistic electron fluxes than more moderate storms. We found that, although it is widely assumed to be true, this was not the case. Over the range of minimum Dst values from –50 to –400 nT the probability that a storm will increase or decrease the fluxes was independent of Dst over the full range of flux ratios.

In contrast when we sort the storms according to the maximum solar wind velocity observed during the event (0-1100 km/s) we find that it is more likely that high-speed solar wind drivers will produce larger increases in the electron fluxes. However, even high-speed events can produce dramatic decreases in relativistic electron populations.

The longest continuous measurements are available from geosynchronous orbit (L≈6.6) and this paper concentrates on that L-shell. However, while the numerical values of the statistics may vary, the general conclusions presented here are valid regardless of the L-shell at which the electron fluxes are measured. Plate 2a shows examples of storms that increase fluxes over the whole outer electron belt while Plate 2b shows an example of a storm that decreased fluxes over the whole outer belt (L≈4–7). Statistically we find that, whether the fluxes are measured at L=4, 5, 6, or 6.6, about half of the storms produce an increase, one quarter produce a decrease, and one quarter produce little change at all (less than a factor of two).

5. Implications for understanding electron acceleration and loss

The results presented here have important implications for forecasting the Earth's radiation environment and its response to moderate or intense geomagnetic storms but they also have implications for our basic understanding of relativistic electron acceleration and loss.

When we compare the pre-storm and post-storm fluxes for these 276 storms we find that there is essentially no correlation between them (Plate 3a). This implies that the fluxes in the radiation belts are not simply "pumped up" during storm times. For essentially any pre-storm flux level the post-storm fluxes could vary over more than two orders of magnitude. Likewise equally intense post-storm fluxes can be produced by pre-existing populations that also range over more than two orders of magnitude.

Of course, acceleration in the radiation belts is a process that energizes lower-energy electrons to relativistic energies, often transporting them across L-shells at the same time. Therefore, comparing pre- and post-storm flux levels at fixed energy and L-shell is not a rigorous technique for quantifying the amount of acceleration in a given event.

In contrast the absolute flux level of relativistic electrons that results from an acceleration event will be a function of the fluxes of the lower-energy source population and, in most acceleration mechanisms, the amount of radial transport as well. Both the intensity of the source population and its location of origin are likely to vary greatly from event to event.

This study re-emphasizes the fact that neither the relative change in fluxes (the flux ratio) nor the absolute post-storm flux level precisely quantifies the amount of acceleration in a given event.

These results also highlight the importance of relativistic electron losses during geomagnetic storms. The losses we discuss here are not temporary, adiabatic responses to the growth and decay of the ring current but, rather, real loss of electrons to the magnetopause or, more likely, to the ionosphere. (Ionospheric loss, i.e. precipitation, is more likely because the losses are observed down to very low L-shell even when the magnetopause remains well outside geosynchronous orbit.)

While about half of moderate or intense storms produce a long term increase in fluxes, the other half either produce little net change or a net loss of fluxes. Consider first the storms which result in little or no change in flux levels. This class of events is observed at all L-shells, all Dst levels, and for all solar wind drivers. It is reasonable to assume that the same acceleration processes that occur during other geomagnetic storms occur during these storms. In which case one must conclude that for some storms the losses of relativistic electrons at a given energy are comparable to the acceleration of “new” electrons to that energy. Likewise, for the one in five storms for which the fluxes at L≈6.6 decrease, it is possible that the loss processes dominate over the acceleration processes.

What emerges from these observations is the suggestion that electron loss and acceleration processes are both enhanced during geomagnetic storms and the fluxes that are observed following the storm are a delicate balance between the amount of acceleration and the amount of loss. Furthermore, it appears that the magnitude of acceleration and loss are comparable, may act simultaneously, and each may have effects that vary by orders of magnitude. Like subtraction of very large numbers, one or another may dominate in a given storm.

It is likely that full and quantitative understanding of the radiation belt response to geomagnetic storms will require full and quantitative understanding of both acceleration and losses of relativistic electrons.

Acknowledgments. We thank Kyoto University for providing the Dst data, the NSSDC for providing solar wind data, and J. B. Blake and the POLAR CEPPAD instrument team for the HIST electron data. We thank the National Science Foundation, the National Aeronautics and Space Administration, and the Los Alamos Institute of Geophysics and Planetary Physics for financial support of this work.

References

Blake, J. B., D. N. Baker, N. Turner, K. W. Ogilvie, and R. P. Lepping, Correlation of changes in the outer-zone relativistic electron population with upstream solar wind and magnetic field measurements, *Geophys. Res. Lett., 24*, 927-929, 1997.

Blake, J. B., J. F. Fennell, L. M. Friesen, B. M. Johnson, W. A. Kolasinski, D. J. Mabry, J. V. Osborn, S. H. Penzin, E. R. Schnauss, H. E. Spence, D. N. Baker, R. Belian, T. A. Fritz, W. Ford, B. Laubscher, R. Stiglich, R. A. Baraze, M. F. Hilsenrath, W. L. Imhof, J. R. Kilner, J. Mobilia, D. H. Voss, A. Korth, M. Gull, K. Fisher, M. Grande, and D. Hall, CEPPAD: Comprehensive Energetic Particle and Pitch Angle Distribution experiment on POLAR, *Space Sci. Rev., 71*, 531-562, 1995.

Friedel, R. H. W., G. D. Reeves, and T. Obara, Relativistic electron dynamics in the inner magnetosphere: A review, *J. Atmos. Solar-Terrestrial Phys., 64*, 265-282, 2002.

Gonzalez, W. D., J. A. Joselyn, Y. Kamide, H. W. Kroehl, G. Rostoker, B. T. Tsurutani, and V. M. Vasyliunas, What is a geomagnetic storm?, *J. Geophys. Res., 99*, 5771-5792, 1994.

Kim, H.-J., and A. A. Chan, Fully-adiabatic changes in storm-time relativistic electron fluxes, *J. Geophys. Res., 102*, 22,107-22,116, 1997.

Li, X., Lepping, J. B. Blake, L. B. Callis, G. Rostoker, H. J. Singer, and G. D. Reeves, Energetic electron injections into the inner magnetosphere during the January 10-11, 1997 magnetic cloud event, *Geophys. Res. Lett., 25*, 2561, 1998.

Meier, M. M., R. D. Belian, T. E. Cayton, R. A. Christensen, B. Garcia, K. M. Grace, J. C. Ingraham, J. G. Laros, and G. D. Reeves, The energy spectrometer for particles (ESP): Instrument description and orbital performance, in Workshop on the Earths Trapped Particle Environment, edited by G. D. Reeves, AIP Press, New York, 203-210, 1996.

Nagai, T., 'Space weather forecast': Prediction of relativistic electron intensity at synchronous orbit, *Geophys. Res. Lett., 15,* 425-428, 1988.

O'Brien, T. P., R. L. McPherron, D. Sornette, G. D. Reeves, R. H. W. Friedel, and H. J. Singer, Which magnetic storms produce relativistic electrons at geosynchronous orbit?, *J. Geophys. Res. 106*, 15,533-15,544, 2001*a*.

O'Brien, T. P., D. Sornette, and R. L. McPherron, Statistical asynchronous regression: Determining the relationship between two quantities that are not measured simultaneously, *J. Geophys. Res., 106*, 13,247-13,259, 2001*b*.

Onsager, T. G., G. Rostoker, H.-J. Kim, G. D. Reeves, T. Obara, H. J. Singer, and C. Smithtro, Radiation Belt Electron Flux Dropouts: Local Time, Radial, and Particle-Energy Dependence, *J. Geophys. Res., in press,* 2002.

Paulikas, G. A., and J. B. Blake, Effects of the solar wind on magnetospheric dynamics: Energetic electrons at the synchronous orbit, in Quantitative Modeling of Magnetospheric Processes, Geophys. Monogr., Amer. Geophys. Un., 21, 180, 1979.

Reeves, G. D., Relativistic electrons and magnetic storms: 1992-1995, *Geophys. Res. Lett., 25*, 1817, 1998.

Reeves, G. D., R. H. W. Friedel, M. G. Henderson, R. D. Belian, M. M. Meier, D. N. Baker, T. Onsager, and H. J. Singer, The Relativistic Electron Response at Geosynchronous Orbit During the January 1997 Magnetic Storm, *J. Geophys. Res., 103*, 17,559, 1998a.

Reeves, G. D., D. N. Baker, R. D. Belian, J. B. Blake, T. E. Cayton, J. F. Fennell, R. H. W. Friedel, M. G. Henderson, S. Kanekal, X. Li, M. M. Meier, T. Onsager, R. S. Selesnick, and H. E. Spence, The Global Response of Relativistic Radiation Belt Electrons to the January 1997 Magnetic Cloud, *Geophys. Res. Lett., 17,* 3265-3268, 1998b.

Reeves, G. D., R. D. Belian, T. C. Cayton, M. G. Henderson, R. A. Christensen, P. S. McLachlan, and J. C. Ingraham, Los Alamos Geosynchronous Space Weather Data For Radiation Belt Modeling, in Radiation Belt Models & Standards, AGU

Monograph #97, J. F. Lemaire, D. Heynderickx, and D. N. Baker eds., 237-240, 1996.
Selesnick, R. S., and J. B. Blake, On the source location of radiation belt relativistic electrons, *J. Geophys, Res., 105*, 2607-2624, 2000.
Williams, D. J., A 27-day periodicity in outer zone trapped electron intensities, *J. Geophys. Res., 71*, 1815, 1966.

R. H. W. Friedel, K. L. McAdams, and G. D. Reeves, Space and Atmospheric Sciences Group, Los Alamos National Laboratory, Los Alamos, NM 87545
T. P. O'Brien, Space Sciences Department, The Aerospace Corp., Los Angeles, CA 90009

(Received XXX; revised XXX;
accepted XXX.)

Paper number 2002GL012345.

Paper number 2002GL012345.

Running Head:

REEVES: RELATIVISTIC ELECTRONS UPS AND DOWNS

Figure Captions

Plate 1. Outer radiation belt electron response to geomagnetic storms and high speed solar wind. The top panel shows 1.2-2.4 MeV electron fluxes (from the POLAR HIST instrument) as a function of L-shell and time. The second panel shows the hourly Dst index with our –50 nT threshold marked in red. The bottom panel shows the solar wind velocity (omni data) with 500 and 600 km/s levels marked.

Plate 2. Details of three types of responses: increase, decrease and "no change". (A) The strong increase of relativistic electron fluxes in response to the January 1997 geomagnetic storm. Two other flux increases are seen in this interval including one for which Dst did not meet our –50 nT threshold. (B) A geomagnetic storm in May 1999 which produced a dramatic and permanent loss of electrons throughout the outer belt. (C) A –100 nT storm in February 1998 with peak fluxes after the storm very similar to peak fluxes after the storm.

Plate 3. Statistics of geosynchronous flux changes for 1989 through 2000. (A) Post-storm peak fluxes and pre-storm peak fluxes are highly uncorrelated showing that the radiation belts are not simply "pumped up" during geomagnetic storms. (B) The distribution of the ratio of post-storm to pre-storm fluxes. About one half of all storms increase the relativistic electron fluxes, one quarter decrease fluxes, and one quarter result in "no change" (changes that are less than a factor of two increase or decrease).

Plate 4. Cumulative probability distributions for the post- to pre-storm flux ratios binned by (A) the strength of the storm measured by minimum Dst, (B) different L-shells as measured by POLAR, (C) the velocity of the solar wind, and (D) phase of the solar cycle. All show both increases and decreases in flux for all values of each parameter. The maximum variation is seen when the data are sorted by solar wind velocity and a somewhat weaker variation is seen with solar cycle.

Plate 1. Outer radiation belt electron response to geomagnetic storms and high speed solar wind. The top panel shows 1.2-2.4 MeV electron fluxes (from the POLAR HIST instrument) as a function of L-shell and time. The second panel shows the hourly Dst index with our –50 nT threshold marked in red. The bottom panel shows the solar wind velocity (omni data) with 500 and 600 km/s levels marked.

Plate 2. Details of three types of responses: increase, decrease and "no change". (A) The strong increase of relativistic electron fluxes in response to the January 1997 geomagnetic storm. Two other flux increases are seen in this interval including one for which Dst did not meet our –50 nT threshold. (B) A geomagnetic storm in May 1999 which produced a dramatic and permanent loss of electrons throughout the outer belt. (C) A –100 nT storm in February 1998 with peak fluxes after the storm very similar to peak fluxes after the storm.

Plate 3. Statistics of geosynchronous flux changes for 1989 through 2000. (A) Post-storm peak fluxes and pre-storm peak fluxes are highly uncorrelated showing that the radiation belts are not simply "pumped up" during geomagnetic storms. (B) The distribution of the ratio of post-storm to pre-storm fluxes. About one half of all storms increase the relativistic electron fluxes, one quarter decrease fluxes, and one quarter result in "no change" (changes that are less than a factor of two increase or decrease).

Plate 4. Cumulative probability distributions for the post- to pre-storm flux ratios binned by (A) the strength of the storm measured by minimum Dst, (B) different L-shells as measured by POLAR, (C) the velocity of the solar wind, and (D) phase of the solar cycle. All show both increases and decreases in flux for all values of each parameter. The maximum variation is seen when the data are sorted by solar wind velocity and a somewhat weaker variation is seen with solar cycle.

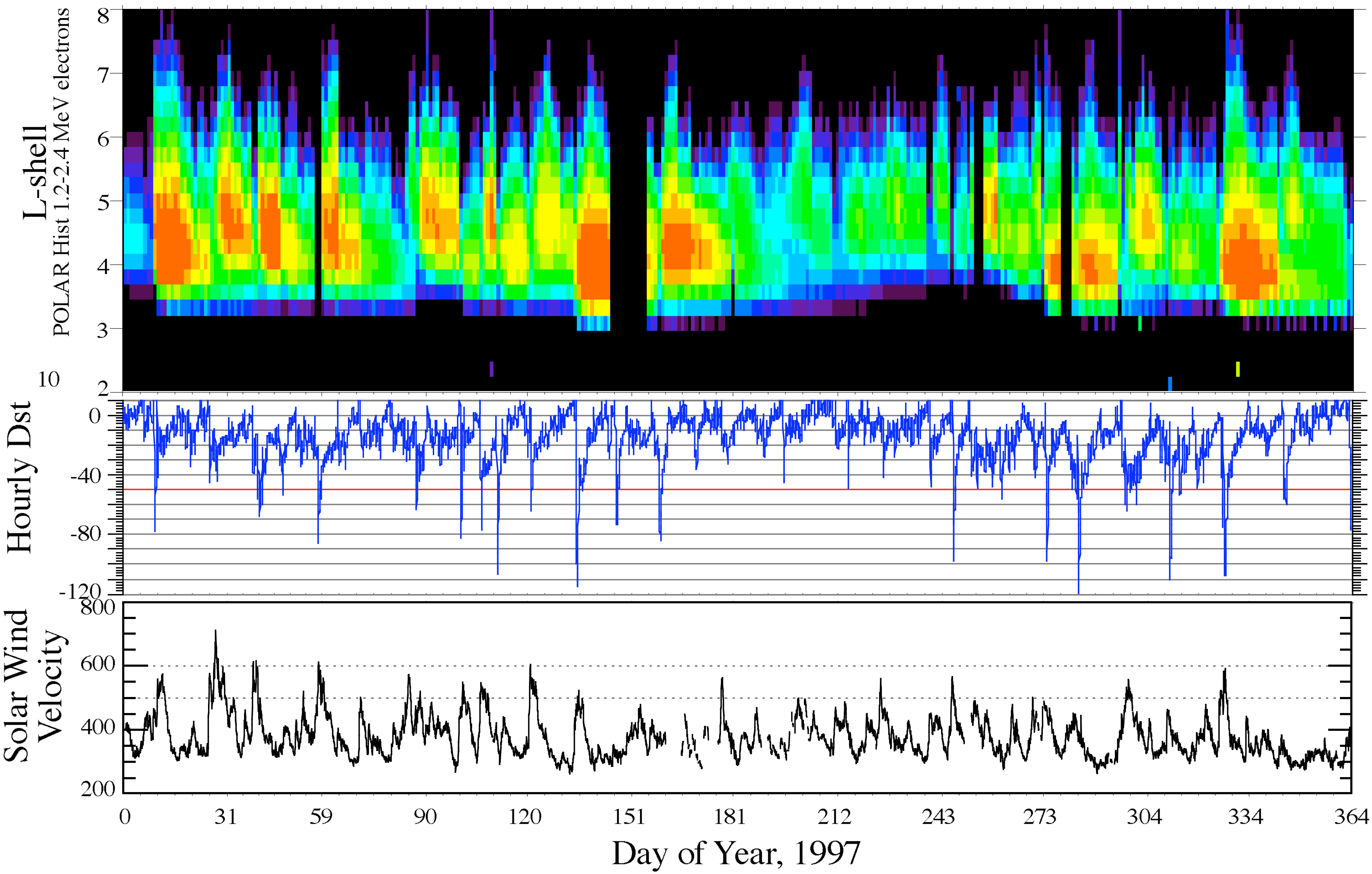
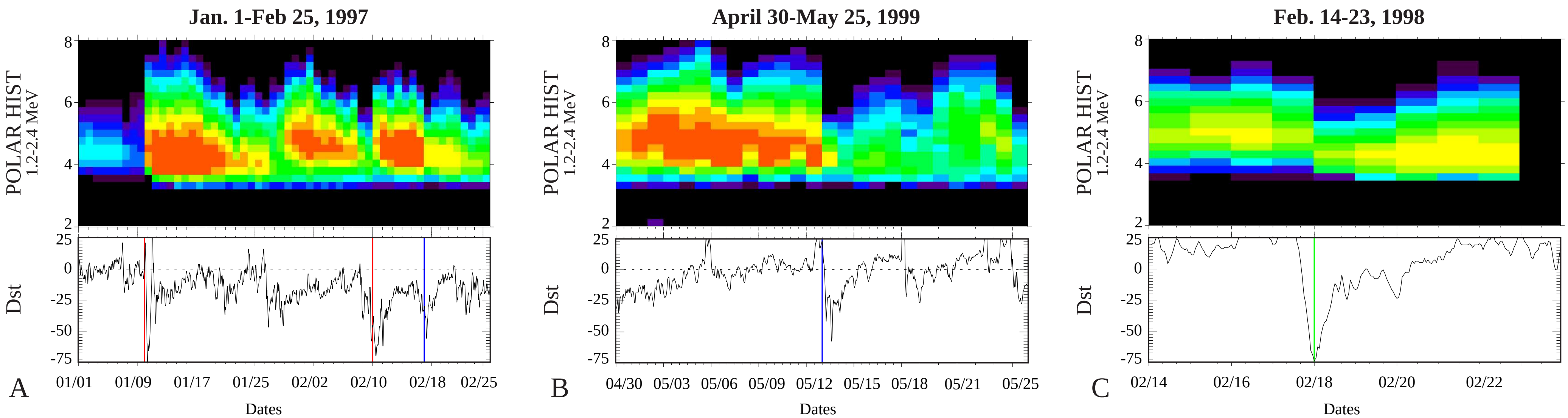
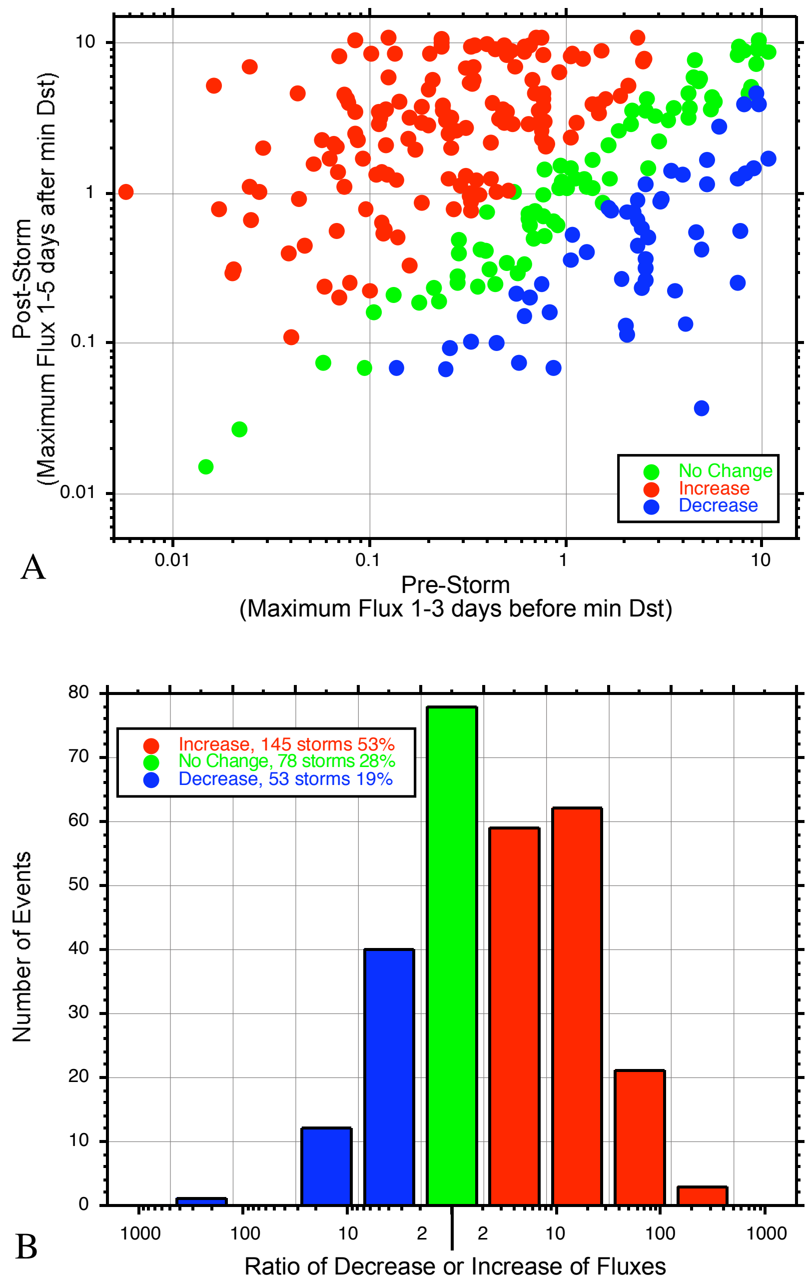

L-shell
POLAR Hist 1.2-2.4 MeV electrons
8
7
6
5
4
3
2
10
Hourly Dst
0
-40
-80
-120
Solar Wind Velocity
800
600
400
200
0
31
59
90
120
151
181
212
243
273
304
334
364
Day of Year, 1997

Plate 1



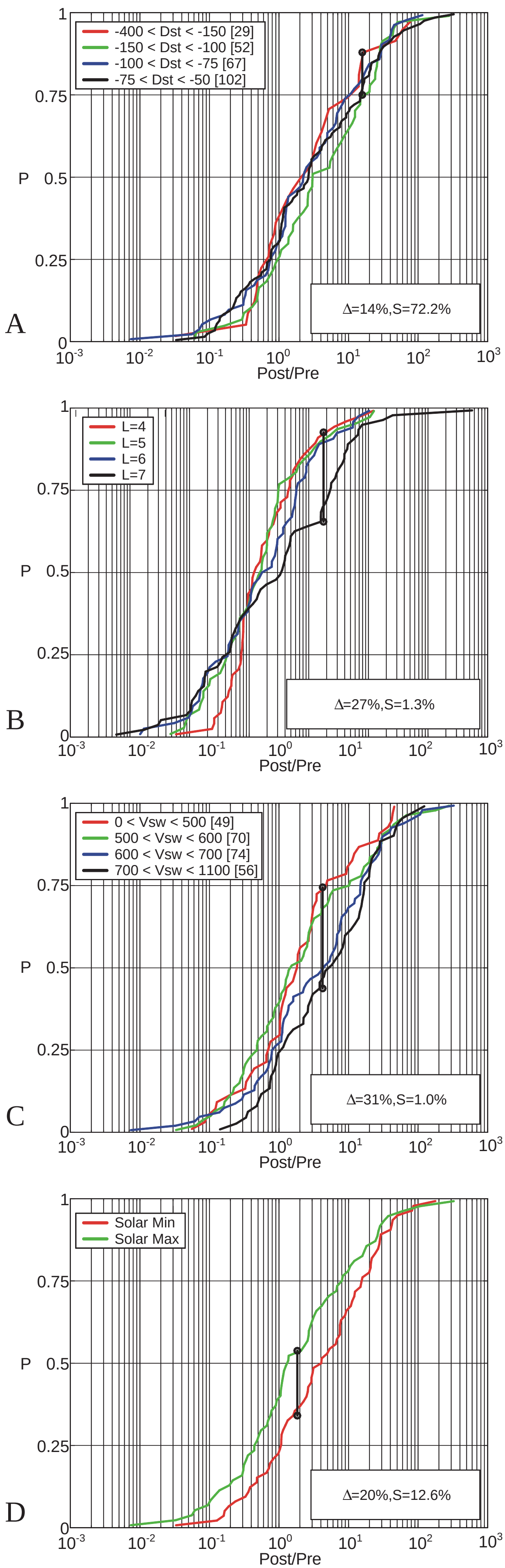
Jan. 1-Feb 25, 1997
April 30-May 25, 1999
Feb. 14-23, 1998
POLAR HIST
1.2-2.4 MeV
Dst
A
B
C
01/01 01/09 01/17 01/25 02/02 02/10 02/18 02/25
04/30 05/03 05/06 05/09 05/12 05/15 05/18 05/21 05/25
02/14 02/16 02/18 02/20 02/22
Dates

Plate 2



A
Post-Storm
(Maximum Flux 1-5 days after min Dst)
Pre-Storm
(Maximum Flux 1-3 days before min Dst)
No Change
Increase
Decrease
B
Number of Events
Ratio of Decrease or Increase of Fluxes
Increase, 145 storms 53%
No Change, 78 storms 28%
Decrease, 53 storms 19%

Plate 3



A
-400 < Dst < -150 [29]
-150 < Dst < -100 [52]
-100 < Dst < -75 [67]
-75 < Dst < -50 [102]
Δ=14%,S=72.2%
P
Post/Pre
B
L=4
L=5
L=6
L=7
Δ=27%,S=1.3%
P
Post/Pre
C
0 < Vsw < 500 [49]
500 < Vsw < 600 [70]
600 < Vsw < 700 [74]
700 < Vsw < 1100 [56]
Δ=31%,S=1.0%
P
Post/Pre
D
Solar Min
Solar Max
Δ=20%,S=12.6%
P
Post/Pre